A SURVEY OF BRITISH RESEARCH ON WAVE PROPAGATION WITH PARTICULAR REFERENCE TO TELEVISION

By R. L. SMITH-ROSE, C.B.E., D.Sc., Ph.D., Member.

SUMMARY

The planning and successful operation of a national television service involve an understanding of the mode of propagation of the radio waves concerned. At the present time the frequency bands provisionally allocated for television broadcasting are located between limits of 41 and 960 Mc/s, and the service at present under development in the United Kingdom is confined to the use of five channels in the band 41–68 Mc/s. For the service to be successful, each transmitting station must establish, over the normal reception area, a satisfactory ratio of the wanted signal to the prevailing noise or other interfering signals. This involves, first, understanding in detail the manner in which the waves carrying the programme signals are propagated within the service area of the station to a radius of the order of 50 to 100 km; and secondly, determining, on a statistical basis, the manner in which the waves from any other station operating in the same frequency channel are propagated to considerable distances in sufficient strength to impair, by interference, reception of the wanted programme.

The paper reviews the results of investigations conducted in this country on the propagation of radio waves of the frequencies assigned for the existing and future television services. Within the service area, this propagation is largely determined by the nature of the terrain over which the waves travel, including the effect of hills and valleys, trees, buildings and similar departures from the ideal smooth-earth condition. The effect of the diffraction of waves round the curved surface of the earth, or over hills, has been studied, as well as the bending of the waves due to the vertical gradient of refractive index in the atmosphere. Within the service area, the field strength from the transmitter remains reasonably constant, but variations may occur as a result of interference between the direct wave and the waves reflected or scattered by moving objects such as aircraft. Apart from such interference, the field strengths attained in practice are in reasonable agreement with those estimated from theory.

In recent years, considerable investigation has been carried out on the propagation of radio waves in the metre waveband (frequencies 30 to 300 Mc/s) at distances of a few hundred kilometres. At such ranges, well beyond the normal optical horizon, the propagation is affected to a major degree by meteorological conditions. The general level of field strength and the variations superimposed on this are determined first by the changes in mean gradient of the refractive index of the atmosphere, and secondly by the presence of temperature inversions which, at heights of one or two kilometres, may act as reflecting layers. Furthermore, at distances approaching the limits of practical reception, turbulence in the atmosphere may be a source of scattering of radio waves and may result in an extension of the normal range of transmission.

Under suitable conditions, transmission of waves in the 30–300-Mc/s band may also take place to distances of several thousand kilometres by way of the ionosphere, but experience suggests that occurrences of reception due to indirect transmission of this kind are comparatively rare with normal transmitter powers and receiver sensitivities.

Apart from the use of radio links at frequencies in the region of 900 Mc/s, comparatively little opportunity has so far arisen for the study of radio-wave propagation in the band 470 to 960 Mc/s, in which much of the future development of television is likely to take place. At higher frequencies, between 3 000 and 10 000 Mc/s, several investigations of wave propagation have been made in the last decade in the course of work connected with the development of centimetre-wave radar. Much of this work was carried out over sea paths, but some of it, conducted over land, has already provided certain information on propagation characteristics, and this will prove of interest in connection with more detailed investigations which are now in progress. It seems likely, however, that the use of such frequencies in a television service will be confined to radio links for point-to-point distribution.

(1) INTRODUCTION

The maintenance and operation of a television broadcasting service involve three main features: first the development of an electric modulating signal from the visual scanning of the scene to be transmitted; secondly, the transmission of this modulation on a suitable carrier wave; and thirdly, the conversion of the received modulated carrier into an image of the scene at the output of the receiver. After preliminary experiments had been conducted on medium frequencies, it became evident early in the history of the subject that the radiation of a service of worth-while quality involved the use of carrier waves of frequencies above 30 Mc/s. The frequency bands which have either been provisionally allocated or are under consideration for use in the European region are 41–68, 174–216, and 470–960 Mc/s. Of these, the lowest band is already in use by the British Broadcasting Corporation for the existing television service and for extensions thereto under development in this country, while various technical aspects of the third band are already being investigated.

From the wave-propagation standpoint, the authority responsible for television broadcasting is interested in three main factors. First, it is desired to know how the field produced by the radiation from the transmitter is influenced by the conditions along the path between the sending station and the receiver at all points within the service area, which is usually of moderate radius—50 to 100 km. Secondly, it is necessary to know to what extent the radiation from a distant transmitter operating in the same or an adjacent frequency channel interferes with this reception within the service area. In this case, the distances of transmission concerned may be several hundreds or even thousands of kilometres; and in so far as the propagation conditions will undoubtedly vary with time, consideration of the phenomena encountered might in this case be confined to the periods normally associated with the transmission of programmes. Thirdly, in so far as radio links on various frequencies of the order of a few hundred or thousand megacycles per second are used to convey television programmes from one point to another in the broadcasting network, the propagation characteristics of the waves of these frequencies also demand attention.

It can be assumed that the specification of the ratio of signal to noise or of wanted to unwanted signal necessary to give an adequate received picture is a matter for the receiver designer to deal with; and further that the exploration of the nature and intensity of the noise interference encountered in various locations, such as those prevailing in quiet rural or noisy urban surroundings, is a matter for study by the engineer concerned with investigating electrical interference.

With this understanding, the paper is confined to a survey

Dr. Smith-Rose is in the Department of Scientific and Industrial Research.

of the work conducted in this country on radio wave propagation over the frequency bands 30 to 10 000 Mc/s and under the particular conditions described above relevant to television broadcasting. From the standpoint of practical application it is convenient to divide the subject into three parts determined by the distance from the transmitter. The first part is concerned with the propagation phenomena encountered within the service area of a television station, and this has come to be regarded in this country as having a mean radius of about 50 km with perhaps 100 km as a maximum. The second part is concerned with transmission to distances from the limits of the service area to several hundred kilometres over which the effect of conditions in the lower atmosphere plays a dominant part in the propagation. The third portion is concerned with the comparatively rare occurrences of propagation to a few thousand kilometres from the transmitter when conditions in the ionosphere are particularly favourable for such transmission.

(2) THE PROPAGATION OF WAVES WITHIN THE SERVICE AREA (50-100 km)

(2.1) Early Work

The study of the propagation characteristics of electric waves in the frequency range 30 to 1 000 Mc/s (wavelengths 10 m to 30 cm) is not by any means of recent origin so far as this country is concerned. Much classical work was in progress at and even before the beginning of the present century. For example, many of Hertz's laboratory experiments on the polarization, reflection and refraction characteristics of such waves were repeated by J. A. Fleming, while G. Marconi demonstrated to the British Association in 1896 the transmission of waves of a frequency of 1 000 Mc/s over distances of a few miles. As, however, the practical use of these very short waves did not appear very promising at that time, little further progress was made until about 1916, when G. Marconi and C. S. Franklin demonstrated some of the possibilities of frequencies of 50 and 150 Mc/s, with suitable directive aerial systems, for point-to-point communication and marine navigation. On the theoretical side, the propagation of electric waves round a perfectly conducting sphere was studied by Lord Rayleigh, H. M. Macdonald, J. W. Nicholson, A. E. H. Love and G. N. Watson; but during the second decade of the century this work became directed towards explaining Marconi's success in transmitting waves of somewhat lower frequencies half-way round the earth's surface. In view of the rapid development of long-distance communication and its dependence on ionospheric conditions, it was natural that much attention should be devoted to an investigation of wave propagation on frequencies below 30 Mc/s, and the related study of the characteristics of the ionosphere in all parts of the world. The advent of broadcasting in the 1920's and the realization that a reliable service depends upon ground-wave transmission provided the incentive for more detailed research on the effect of the earth's surface on radio-wave propagation. While this naturally began on the medium frequencies then in use for broadcasting in the region of one megacycle per second, much useful information was obtained on propagation characteristics and the electrical properties of the ground, and this has afforded the basis of the continued work at higher frequencies.

(2.2) Transmission of Waves over a Smooth Earth

One of the most important matters to note in studying the transmission of waves on frequencies above 30 Mc/s is that the aerial system is usually erected above the ground at a height of many wavelengths. In these circumstances it is evident that, for short-distance transmission over the ground, there are two possible paths along which the waves can travel between the
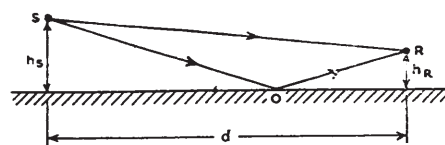

Fig. 1.—Direct and ground-reflected rays.

sender and receiver, as shown in Fig. 1. The general conditions relating to the received field strength may then be stated in the following terms.

The direct radiation from S to R will give rise to a free-space field at R of

$$\mathscr{E}_0 = \frac{60\pi lI}{\lambda d} \qquad \qquad (1)$$

where l is the effective length of the aerial carrying the current I, λ is the wavelength and d is the distance of transmission, and the relevant units are volts, amperes and metres.

If the sending aerial is a half-wavelength dipole with a current I at its centre, eqn. (1) reduces to

$$\mathscr{E}_0 = \frac{60I}{d} \qquad \qquad (2)$$

To this field must now be added vectorially the corresponding field due to the radiation along the path SOR, and the complex reflection coefficient of the ground at O must be taken into account. For a plane earth, the resultant field at R is therefore

$$\mathscr{E} = \mathscr{E}_0[(1 + \rho\epsilon^{-j\phi}) \qquad \qquad (3)$$

where ρ is the appropriate reflection coefficient of the ground, ϕ ($= 4\pi h_S h_R/\lambda d$) is the phase difference between the two sets of waves arriving at the receiver, and h_S and h_R are the heights of the sender and receiver respectively above the ground.

Eqn. (3) indicates that while d remains small or comparable with the heights h_S and h_R, the resultant field $\mathscr{E}$ passes through alternate maxima and minima as the phase difference ϕ passes through odd and even multiples of π, the most distant maximum occurring when $\phi = \pi$. In nearly all cases of practical interest the receiver is well beyond this maximum, and the distance d is so large that the reflection coefficient ρ approaches -1 for either horizontally or vertically polarized waves. As a result of these conditions eqn. (3) reduces to

$$\mathscr{E} = \mathscr{E}_0 \frac{4\pi h_S h_R}{\lambda d}$$

or, in practical terms,

$$\mathscr{E} = 90\sqrt{(P)} \frac{h_S h_R}{\lambda d^2} \qquad \qquad (4)$$

where $\mathscr{E}$ is the field strength in volts per metre, P is the radiated power in watts, and h_S, h_R, λ and d are all measured in metres.

This is the basic equation relating to the propagation of short electric waves over a smooth plane earth with no refracting atmosphere along it. In practice eqn. (4) requires modification to take into account (a) the attenuation due to the imperfect conductivity of the earth, (b) the fact that the earth is spherical and not flat, and (c) the fact that a large part of it is covered with hills and valleys, rivers, railways and buildings. Also, as we shall see, at the frequencies in which we are now interested, the vertical gradient of atmospheric conditions plays an important part in determining the field actually received at any time.

(2.3) Metre-Wave Propagation along the Ground

The fundamental study of the propagation of waves in the metre band (frequencies 30 to 300 Mc/s) in this country has progressed along several distinct lines simultaneously. For

example, in 1931, R. L. Smith-Rose and J. S. McPetrie[1] described some experiments made on frequencies between 32 and 54 Mc/s over a distance of about 700 m across a flat field at the Radio Research Station, Slough. It was shown that for distances greater than about 200 m, the measured field-strength decreased approximately inversely as the square of the distance, as indicated by eqn. (4), although the actual results were somewhat affected by the presence of trees. Qualitative observations were continued to distances reaching 32 km; but these were very considerably augmented by J. S. McPetrie and J. A. Saxton,[2] who made comprehensive measurements of the field strength at distances up to 40 km in various directions from a sender at Teddington working on frequencies of 100 and 143 Mc/s (wavelengths 3 and 2·1 m). Their results illustrated the general validity of eqn. (4) for both vertical and horizontal polarization, and also the extent to which departures from the theoretical values may be due to irregularity of the ground and the presence of trees and buildings.

To assist in comparing the experimental results with the appropriate theoretical formulae, it was early realized that more detailed information was required on the reflection coefficient of the different types of ground encountered in practice. This could be obtained either by direct measurement of the reflection coefficient, such as was done by McPetrie[3] under vertical-incidence conditions, or by deduction from a knowledge of the electrical properties of the earth's surface. It was to this end that laboratory measurements of different samples of the soil taken from various parts of Great Britain were made at frequencies up to 100 Mc/s by Smith-Rose,[4] and that direct measurements of the attenuation of waves of frequencies 60 and 150 Mc/s were made through grass-covered sandy loam, by McPetrie and Saxton.[5] Furthermore, McPetrie[6] constructed a series of curves from which the complex reflection coefficient of the earth's surface can be read for a wide range of values of electrical properties, frequencies and angles of incidence. The same investigator, at a later date and in collaboration with Miss A. C. Stickland,[7] supplemented these curves with a further series indicating in more detail the phenomena occurring within a few degrees of grazing-incidence transmission, and for both vertical and horizontal polarization.

More recently, G. Millington[8] has investigated the phenomena which accompany the transmission of vertically polarized radio waves along ground of which the electrical characteristics change suddenly, as they do from land to water at a river estuary or a coast-line. It was shown theoretically and confirmed experimentally that as the waves travel from land across the water there can be an appreciable rise in field strength, to a maximum occurring some distance from the land. In experiments made at a frequency of 75 Mc/s (wavelength 4 m), G. Millington and G. A. Isted[9] showed that, on receding from the transmitter across a boundary from land to sea, the received field-strength increased by some 10 db above its value at the boundary at a distance of about 500 m from it. This effect is obviously of great importance in determining the extent of the service area of a station using vertical polarization in directions in which the terrain includes rivers, estuaries or short sea paths.

(2.4) Diffraction of Waves around the Curved Surface of the Earth

So far we have considered the earth as sensibly a plane surface. While this description might apply to a large portion of the service area of a television station, such an area in general includes hills and ridges, and the effect of these must be taken into account in determining what conditions will be like for reception on and beyond such obstacles to optical path transmission.

For the case of transmission over a smooth spherical earth, the simple formula given in eqn. (3) for a plane earth becomes modified to the form

$$\mathscr{E} = \mathscr{E}_0(1 + D\rho\epsilon^{-j\psi}) \qquad . \qquad . \qquad . \qquad (5)$$

In this equation, D is a divergence factor expressing the reduction in field strength of the ray reflected from a convex surface, and the phase difference between the direct and reflected rays is

$$\psi = \frac{4\pi k h_S h_R}{\lambda d}$$

where k is a fraction, like D, determined by the curvature of the earth. It may be noted that both D and k are unity for plane earth conditions; and that, for a spherical earth, both tend to zero as the distance between sender and receiver approaches the limiting optical range.

Now the subject of diffraction, or the bending of radio waves around the curved surface of the earth, has been studied by many theoretical workers during the last forty years, and notable contributions have been made to the subject in this country by T. L. Eckersley[10] and G. Millington.[11] The diffraction formula resulting from this work gives the field strength as the sum of an infinite series, which it is tedious to calculate numerically for distances just beyond the limit for which the simple reflection formula [eqn. (5)] is applicable. For distances well beyond the optical range, however, only one term is really necessary to give the accuracy usually required. Much of the discussion of the theoretical workers has been concerned with the method of joining together the two curves relating field strength and distance from sender, first within the optical range where the ray theory explained above applies, and secondly at great distances where the simplified diffraction formula is applicable.

The curves adopted by the C.C.I.R.[12] in 1937 were based on the contributions of Eckersley and Millington and the corresponding work of B. van der Pol and H. Bremmer.[13] These curves cover the frequency range 30–150 Mc/s, and are presented in such a form as to show the gain in field strength at any distance effected by raising the sending or receiving antenna. As Eckersley has emphasized elsewhere,[14] such "height/gain" curves are only applicable to the condition in which reception takes place at distances well beyond the horizon from the transmitting station aerial. The C.C.I.R. curves were revised and extended for frequencies up to 10 Mc/s only, at the Plenary Meeting held in Geneva 1951, the Proceedings of which have recently been published.[54]

A further contribution to the theoretical aspects of this subject was published in 1947 by C. Domb and M. H. L. Pryce;[15] in this paper they paid special attention to the conditions prevailing at and just beyond the optical cut-off point, as well as to those for transmission to greater distances. They gave convenient curves and formulae for the calculation of field strength at any height and distance from the transmitter, and pointed out that the rate of attenuation beyond the optical horizon is 17·6 db per unit of a "standard distance" d_0, defined by the expression $d_0 = (R^2\lambda/\pi)^{\frac{1}{3}}$, where R is the radius of curvature of the obstacle and λ the wavelength, all dimensions being in metres.

Now, in an extension of the experimental work already referred to, J. S. McPetrie and J. A. Saxton[16] examined in some detail the diffraction of waves over hills with a long ridge formation and reasonably clear of trees. They showed that within the immediate shadow of a ridge, the field strength from a distant sending station decreased less for vertical than for horizontal polarization. When, however, the receiver was raised to a position above the shadow of the hill, the field was greater with horizontally than with vertically polarized waves. These experimental results

are seen to be similar to the conclusions reached both theoretically and experimentally on the diffraction of light waves by a straight edge, when it is borne in mind that the radius of curvature of the ridge is large compared with the wavelength.

Further experimental work was carried out by J. S. McPetrie and L. H. Ford[17] to test the suitability of the theoretical formula given by Domb and Pryce. Experiments were conducted over the crest and well into the shadow of two hills, selected as being approximately semi-cylindrical in contour and free of trees; the radii of curvature of the two hills were approximately 3 300 m and 380 m. Remarkably close agreement was obtained between the theoretical and measured attenuation curves on various frequencies between 27 and 3 250 Mc/s (wavelengths 11·15 m to 9·2 cm). For frequencies below 600 Mc/s, the previous conclusions—that vertically polarized waves give better signals in the shadow while horizontal polarization is better out of the shadow—were confirmed. At the highest frequencies, however, no appreciable difference was found between vertical and horizontal polarization as the receiver was moved over a ridge.

(2.5) Reflection and Scattering of Waves

D. I. Lawson[18] has discussed the form of interference to which television reception is subject by reason of the arrival of waves by more than one path. For example, in addition to the reception of waves along the direct path from the transmitter, waves may arrive along an indirect path after reflection from fixed obstacles such as buildings, trees and metallic sheets and wires. The longer path travelled by such indirect waves introduces a delay into the picture signal, which portrays itself on the screen of the receiver as a "ghost" image of the main picture. Lawson analysed the conditions giving rise to such interference and showed that the locus of a reflector giving a fixed-delay form of interference is an ellipse with the transmitter and receiver at the focal points. Such interference in television reception is not unknown, particularly in areas where the main signal is rather weak, but little experimental work appears to have been done in this field.

Some investigations have, however, been made on the corresponding phenomena in the allied field of radio direction-finding at very high frequencies. The bearings observed on direction-finders are very susceptible to changes when waves are received along more than one path. H. G. Hopkins and F. Horner[19] have conducted some detailed research in this subject; and they have reported cases of the reception of echo signals with time delays up to 10 microsec due to reflection of waves from a large gasholder and a range of hills at distances of 12 to 30 km respectively. Experience in this field led Horner[20] to carry out a more detailed investigation of the scattering of waves by metal wires and sheets at a frequency of 600 Mc/s. Such effects do not, of course, arise only from fixed objects; the effect of a passing aircraft in producing a fluctuating image on a television screen is a matter of general experience.

(2.6) Refraction of Waves in a Standard Atmosphere

In 1893, Lord Rayleigh[21] considered the problem of the refraction in the earth's atmosphere of incoming rays of light from stars and other celestial bodies. It has thus been well known throughout the history of radio development that the atmosphere can act as a refracting medium and bend waves passing through it, but this phenomenon has not been of any great significance in the use of frequencies below 30 Mc/s. In 1914, J. A. Fleming[22] discussed the deviation of electromagnetic waves by refraction in the atmosphere caused by the decreasing density of the constituent gases with increasing height above the earth's surface. It was pointed out that a ray starting from a point on the earth and tangential to its surface at that point would be bent in passing through the atmosphere and follow a curved path concave to the earth itself. Later T. Y. Baker[23] gave a detailed analysis of the refraction of electric waves in travelling through a spherically stratified medium, such as the atmosphere, in which the refractive index varies uniformly with height. Experimental evidence for the existence of such refraction soon became available when, about the year 1930, several radiocommunication links were established in various parts of the world on frequencies of about 40 Mc/s and above, over ranges that were well beyond the geometrical horizon distances. At that time the effect of atmospheric refraction was chiefly appreciated by the resultant fluctuation of received signal strength. It is proposed to pursue this particular aspect of the subject in the next part of the paper; here we are concerned with the way in which "standard" refraction conditions, as they are now termed, may influence wave propagation within the service ranges under consideration.

The refractive index of the atmosphere is given by the expression

$$(n - 1) \times 10^6 = \frac{80}{T}\left(P + \frac{4\,800p}{T}\right) \qquad . \quad . \quad . \quad (6)$$

where n is the refractive index, T the absolute temperature, P the atmospheric pressure in millibars, and p the partial pressure of the water vapour in millibars. Under all conditions normally encountered in the lower atmosphere, the value of n is a few hundred parts in a million greater than unity. While this absolute value of the refractive index is not of great importance, it is now well established that small variations in its value, even of one or two parts in a million, may be a determining factor in the phenomena associated with the transmission of radio waves.

When considering the path of radio waves transmitted between any two points it is necessary to realize that the refraction takes place relative to a curved earth. Hence it has become the practice among workers in this field to make use of an excess modified refractive index (or refractive modulus), M, defined by the equation

$$M = \left[(n - 1) + \frac{h}{a}\right] \times 10^6 \qquad . \quad . \quad . \quad (7)$$

where a is the radius of the earth and h the height of the point of observation above the earth.

The rate of variation of M with height under any given meteorological conditions then determines the bending of the radio waves relative to the earth, and this affects the amplitude of the signal ultimately reaching the receiver. It will thus be clear that the refraction or bending of waves in the lower atmosphere depends upon the vertical gradient of the temperature, T, and humidity, p, of the air along the path of transmission. While experimental evidence has been given by C. R. Englund, A. B. Crawford and W. W. Mumford,[24] that at distances of less than 64 km radio waves of frequencies of 75 and 150 Mc/s are subject to some variation with changing atmospheric conditions, this is usually regarded as a negligible effect in transmission over geometrically optical paths. It is, however, important to consider to what extent there is steady and continuous refraction of the waves under what may be termed "standard" atmospheric conditions. Now, the meteorologists specified some years ago a "standard atmosphere" for aeronautical purposes, but, as was pointed out by A. C. Best,[25] this does not take account of the varying humidity of the air and so is not directly suitable for the definition of a "standard radio atmosphere." While alternative proposals have been put forward and discussed between meteorologists and radio investigators, the definition now in

common use, and adopted by the C.C.I.R. at Geneva in 1951, is that published by the British Standards Institution.[26] Here the standard radio atmosphere is defined as the atmosphere which will give rise to a negative gradient of refractive index of $0·12$ M-unit per metre, where M is given by eqn. (7).

Now, in travelling through an atmosphere of such a uniform gradient, radio waves emitted in a substantially horizontal direction will follow a curved path, which is approximately a circle of radius equal to $1·3$ times the radius of the earth. It will be appreciated that the effect of such refraction must be added to that of the diffraction discussed in Section 2.4, in order to determine the variation of field strength with distance for radio waves transmitted round a smooth spherical earth. Fortunately, it is a relatively simple matter to estimate these combined effects by the method proposed by T. L. Eckersley,[10] who showed that the phenomenon of refraction could be taken into account by increasing the value of the radius of the earth in the diffraction formulae to give a value defined by B.S.I. as the "effective radius of the earth." For the standard radio atmosphere defined above, the effective earth radius is four-thirds of the actual radius; and this value is now in common use by radio engineers for calculating propagation conditions and service areas of transmitting stations.

(2.7) Application of Knowledge of Propagation to Practical Engineering

The object of conducting investigations on wave propagation on the lines described here is chiefly to provide the radio engineer with a general understanding of the characteristics of radio waves under some of the many conditions met with in practice. It is not to be expected that the results of such fundamental research will enable a complete forecast to be given of the field strength likely to be received at all points within the service area of a given transmitter. The knowledge acquired does, however, facilitate initial studies of the relative merits of a number of possible sites for a sending station, and of the effect of the terrain in open country, or of buildings in an urban area, on the reception conditions. It will be clear that a transmitting station should in general be installed at as high a point as possible somewhere near but not necessarily at the centre of the desired area; the site should be in such a position that, for example, intervening mountains do not cast shadows over concentrated built-up areas which it is desired to serve.

The initial survey carried out in this way must then be supplemented by carrying out actual field-strength measurements around experimental transmitters set up on the sites selected for further investigation. Only in this way can an accurate forecast be made of the service area of the transmitting station which it is finally decided to plan and install. This procedure is dealt with in some detail by L. F. Tagholm and G. I. Ross[27] in their accompanying paper, which discusses the problem of covering the United Kingdom with a television service using the frequency band 41–68 Mc/s. The study of reception conditions on the actual installation is usually carried out as soon as the main transmitter and aerial system are available, and before it is opened to the public service. The results of the study are presented in the form of contour maps showing the measured field-strength at the receiving points about 10 m above ground level, and for a specified condition, usually peak-white, of the vision transmitter. Such contour maps have already been published for the London (Alexandra Palace)[28] and the Birmingham (Sutton Coldfield)[29] transmitting stations, and some very detailed results, with the corresponding contour map, of a field-strength survey conducted around the Wrotham experimental station operating on 90 Mc/s have been published by H. L. Kirke, R. A. Rowden and G. I. Ross.[30]

All these published curves and maps show to a very marked degree the effect of hilly country or built-up areas on the field strength received at different distances around the transmitter. It has been demonstrated by several investigators that the effect of different types of terrain on the received field-strength is such as to result in the logarithm of this field strength being normally distributed about a median value at a given distance from the transmitter. The standard deviation of the field-strength distribution lies generally in the range 10–20 db, depending upon the nature of the terrain and varying from undulating, open country to part of a built-up area. It is of interest to compare values in this range with those quoted by R. M. Wilmotte[31] for the corresponding conditions in the United States. Following the practice of the Federal Communications Commission, Wilmotte uses the "slope" of the log field-strength distribution curve, defined as the ratio between the 99% point and the 50% point. He quotes values of this slope as 42 for city areas and 27 for rural areas, and these correspond to standard deviations of 12 and 18 db respectively, which are within the range mentioned as applying to this country.

Moreover, if the effective heights of the aerials above ground at the sending and receiving terminals are appropriately chosen, it is often found that the median values of field strength at various distances from the transmitter fit the smooth-earth theoretical curve reasonably well. This is illustrated in Figs. 2 and 3, which
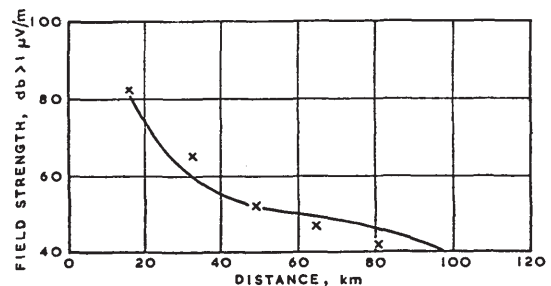
Fig. 2.—Field strengths in the Alexandra Palace service area (45 Mc/s).

——— Calculated for smooth-earth propagation, with h_S = 183 m, h_R = 9 m.
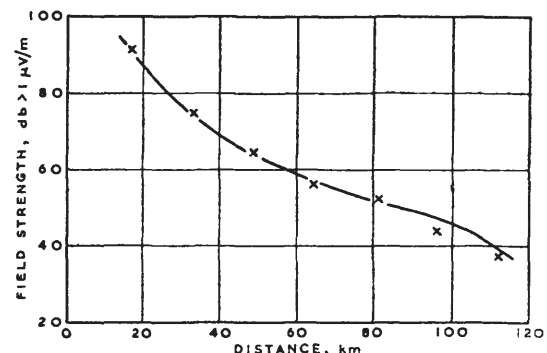× × × Observed (median values).

Fig. 3.—Field strengths in the Sutton Coldfield service area (61·75 Mc/s).

——— Calculated for smooth-earth propagation, with h_S = 213 m, h_R = 9 m.
× × × Observed (median values).

are derived from field-strength measurements (vision channel) made by the B.B.C. in the areas served by the Alexandra Palace and Sutton Coldfield transmitters respectively. In each case the effective receiving-aerial height above ground is taken as equal to the actual value of 9 m, and the sending-aerial height (h_S), for which the theoretical curves are drawn, has been determined by making experiment and theory fit at a distance of 16 km from each transmitter. The two theoretical curves are

derived simply on the basis of diffraction round a smooth earth of effective radius four-thirds of the geometrical value, and correspond to the actual powers radiated by the transmitters; the experimental points are the median values referred to above.

The height of 183 m derived for h_S at Alexandra Palace is in fact the sum of the mast height above ground and the site height above sea-level (each about 90 m); it would thus appear that in the Alexandra Palace service area the average effective height of the sending aerial is the actual height above sea-level. On the other hand, for the Sutton Coldfield service area it appears that the effective value of h_S is 213 m, which is about the height of the sending aerial above ground at the site of the transmitter. An inspection of the general topography in the two service areas would lead to the conclusion that the overall effective values of h_S would be of the order indicated.

The agreement between theoretical and measured field-strengths is significantly better in Fig. 3 than in Fig. 2; this is probably due to the fact that the data from which the Sutton Coldfield median values were deduced were much more extensive (and represented a better statistical sample) than those used for the Alexandra Palace area.

(3) THE PROPAGATION OF METRE WAVES THROUGH THE LOWER ATMOSPHERE

(3.1) Atmospheric Variations and Signal Fading

The standard conditions of refraction referred to in Section 2.6 are those which occur in a well-mixed atmosphere where the pressure, temperature and absolute humidity decrease with height, and where, as a consequence, the refractive index of the atmosphere decreases steadily and uniformly with height above ground. Since the gradient of refractive index is greater for radio waves than for light waves, useful transmission to perhaps a little beyond the optical horizon is to be expected, because the rate of attenuation in the diffraction region at metre wavelengths is very high. It was, however, noticed some twenty years ago that metre waves were often transmitted to much greater distances, and that in general a fading signal was obtained beyond the horizon, though the frequency and range of fading varied between wide limits. Such phenomena were observed by Jouaust[32] in 1930 on a 60-Mc/s radio link of about 200 km between Nice and Corsica. In this country the Department of Scientific and Industrial Research carried out experiments in 1931, using transmissions from the Post Office station at Rugby on a frequency of 54·5 Mc/s.[33] Signals were received beyond the horizon at a distance of 70 km, and a distinct diurnal variation of signal strength was observed. It was found that on a hot day the strength gradually diminished towards noon and attained a minimum at about 1400 G.M.T., gradually increasing thereafter until the early-morning strength was regained at about 1800 G.M.T. A few years later R. A. Hull,[34] who experimented with transmissions on a frequency of 60 Mc/s, noted a correlation between his measurements of field strength and weather conditions over the propagation path. Hull particularly drew attention to the existence of unusually strong signals at long range in the presence of temperature inversions.

Since the early 1930's further investigations of propagation at metre wavelengths, carried out particularly in the United States and in this country, have served to confirm and extend the above results. It is now well known that the refractive-index height profile of the lower atmosphere, which is a most important factor in the determination of propagation characteristics at very high frequencies, is itself considerably modified by changes in meteorological conditions.

In 1943, R. L. Smith-Rose and Miss A. C. Stickland[35] described a study of propagation at frequencies of 37·5 and 60 Mc/s over

the Post Office radio-telephone link between Guernsey (C.I.) and Chaldon, Dorset. The transmission path was almost entirely over sea and was about 137 km in length, of which nearly 60 km was outside the optical range. This investigation showed that, while the fading of the signals was similar in type on the two frequencies, there was a difference in the secular variation of the amount of fading on 37·5 and 60 Mc/s. No diurnal variation of signal strength was noted, in contrast with the general experience in propagation over land; in addition there seemed to be no evidence of any seasonal variation in intensity. Consecutive days occasionally showed a change in general signal level of as much as 20 db, while instantaneous changes of field strength reached 60–80 db at times. The general conclusion was reached that abrupt changes in temperature and water-vapour gradients in the atmosphere give rise to signal variations in good weather, whilst the absence of these discontinuities in bad weather leads to steadier signal conditions.

During the period of the recent war there was a tendency to concentrate effort on studying propagation phenomena at centimetre wavelengths in view of the marked abnormalities in radar performance at these wavelengths attributable to tropospheric influences. The relation between such abnormalities and weather has been discussed in some detail by H. G. Booker.[36] Since 1945, interest in the general use of very high frequencies has returned, and further investigations on wave propagation at these frequencies have been conducted.

Two papers[37] dealing with the propagation of metre waves over land, and beyond the normal horizon, have recently been published in the *Proceedings* of The Institution. The first of these papers, by J. A. Saxton,[37(a)] is a theoretical examination of the manner in which variations in the refractive-index structure of the lower atmosphere can affect propagation, with particular reference to the frequency band 40–90 Mc/s. These variations may lead to increased general refraction near the surface of the earth, producing, in the limit, guided-wave or duct transmission, or to partially reflecting inversion layers at heights ranging from a few hundred to one or two thousand metres. Consideration has also been given to the possible significance of the scattering of radio energy at metre wavelengths by turbulent eddies in the atmosphere. For aerial heights up to, say, 100–200 m, and particularly in transmission over broken country, it seems probable that abnormally high field-strengths at distances of a few hundreds of kilometres are more likely to be a consequence of reflection at high-level inversion layers than of increased refraction near the surface of the earth, or of scattering arising from atmospheric turbulence, though such scattering may well be the dominant factor at even greater distances.

The influence of atmospheric turbulence in scattering very short radio waves had previously been discussed by E. C. S. Megaw,[38] who suggested that such scattering might be one of the factors determining the signals received from high-power metre-wave transmitters (including those used for television) at distances greater than about 160 km.

The second of the papers referred to, namely that by J. A. Saxton, G. W. Luscombe and G. H. Bazzard,[37(b)] describes experimental investigations on long-range propagation over land at frequencies of 45 and 90 Mc/s, and shows how the measurements of field strength may be interpreted in the light of the considerations presented in the first paper. The lengths of the transmission paths investigated varied from 110 to 270 km, and the range of fading increased with distance, as might have been expected; a diurnal variation was found on all links. Although much more detailed knowledge of the prevailing meteorological conditions would have been desirable, it was possible to show that, over paths of 110 km (on 90 Mc/s) and 160 km (on 45 Mc/s), the strongest signals were almost certainly caused by reflection

at elevated inversion layers. The geometry of transmission over the longest path (270 km) was such that a definite discrimination between the different modes of propagation could hardly be achieved, especially in view of the lack of detail in the available meteorological data. It seemed reasonably certain, however, that atmospheric scattering was not important over any of the paths investigated.

(3.2) Range of Transmission under Standard and Non-Standard Tropospheric Conditions

Although it is found that variations in atmospheric refraction can sometimes produce significant fading (10–20 db) at very high frequencies at points within the radio horizon, and therefore towards the edges of the service area of a television station, the normal service area is in fact fairly well defined in terms of propagation under standard conditions of refraction. For example, an examination of the field-strength contours around the existing television stations shows that, in general, a field strength of 500 μV/m (at a receiving-aerial height of 10 m) may be expected to a distance of about 80 km, and such a field strength should give reasonable reception in noise-free areas. By way of comparison, calculation shows that under ideal conditions of propagation over a smooth earth, with standard atmospheric refraction, the field strength of 500 μV/m, at $h_R = 10$ m, would be established at a distance of 80 km by a transmitter radiating 100 kW from a half-wavelength aerial at a height of 200 m above ground; this radiation is typical of the output of modern high-power transmitters in the United Kingdom.

The range of transmissions from a television station under non-standard conditions of refraction is much less readily defined. Although meteorological conditions in the lower atmosphere are often such as to produce abnormally high field-strengths beyond the horizon, such super-refraction can hardly be relied upon to give any worth-while increase in the normal service area of a station. Sub-standard refraction in the troposphere occurs less frequently than super-refraction, and does not, in any case, produce serious reductions of field strength within the service area. Super-refraction, however, must be taken into account in determining the minimum allowable spacing between two transmitters operating on common or adjacent channels. This problem is dealt with in some detail in an accompanying paper by J. A. Saxton.[39]

(3.3) The Effect of Long-Distance Transmission on Television Services in the Same or Adjacent Channels

Considerable experience has by now been gained of the influence of the weather on v.h.f. propagation, but it is not yet possible to predict exactly the transmission conditions even if the weather over the path concerned could be accurately forecast. It is clear, therefore, that from the point of view of the radio engineer a statistical approach to the problem is the only really satisfactory one. During the last few years extensive observations have been made in this country, and are continuing to be made, mainly by the British Broadcasting Corporation, the Post Office and the Department of Scientific and Industrial Research, in order to arrive at statistics covering the long-range transmission of metre waves, so that frequency allocations for stations working in this band may be made on a sound basis.

The required statistical information on propagation cannot yet by any means be said to be adequate, but the order of magnitude of the phenomena to be expected is becoming clear. For example, existing measurements indicate that, for perhaps as much as 10% of the time, a signal strength may occur at distances of from 250 to 350 km equal to that occurring at only 150 km under standard conditions of refraction.

With the limited number of frequency channels at present available for television, it has become necessary to plan for the duplication of frequencies, even to provide for only a reasonably satisfactory coverage of the United Kingdom. It is thus necessary to know the degree of interference likely to be experienced in the local service area of a given station caused by long-range transmission from a distant station on the same (or an adjacent) frequency. It may be noted, too, that the problem becomes still more complex when it is remembered that the rest of Western Europe is also involved in the allocation of frequencies in the same band.

In any attempt to estimate the required minimum spacing of common-frequency stations, it has first to be decided what constitutes intolerable interference—a matter which is obviously partly subjective, but which also depends upon the system of synchronization, if any, used for the two transmitters. When all relevant factors are taken into account it would appear that the necessary ratio of wanted to unwanted signal may lie anywhere within the range 20–50 db according to the circumstances. The permitted level of an interfering signal having been determined, it is finally necessary to specify for what fraction of time this level shall not be exceeded, since the station spacing required to give complete immunity from interference may be quite impracticable.

In the Convention paper by J. A. Saxton[39] an analysis has been made of the data on long-range transmission obtained by the B.B.C., the Post Office and the D.S.I.R., and their bearing on common-frequency station spacing has been pointed out. In the absence of variations in tropospheric refraction, one might normally have expected a spacing between such stations of perhaps 250–350 km depending upon the field strength to be protected and the degree of protection from interference required. It appears, however, that as a consequence of super-refraction in its varied forms these spacings should be at least in the range of 350–600 m. It must be borne in mind that conditions in the troposphere vary considerably in different parts of the world. While this discussion relates to the temperate conditions in the United Kingdom, any conclusions derived therefrom may require considerable modification if they should be applied to localities where different climatic conditions prevail.

(4) IONOSPHERIC INFLUENCES AND LONG-RANGE RECEPTION

It has long been known that under appropriate conditions the density of ionization in the ionosphere is sufficient to support the transmission of radio waves at frequencies within the range 30–50 Mc/s. For example, during the years 1929–32, fairly regular reception was obtained at the D.S.I.R. Radio Research Station, Slough,[40] of transmissions occurring on the Rome–Sardinia radio-telephone link on two wavelengths near 10 m (30 Mc/s), the distance of these stations from Slough being about 1 500 km. The signals were, in general, audible in the daytime only between the months of May and October. Reception was less frequent during the summer of 1933 than during that of 1932, an effect attributed to the approach of the minimum of the sunspot cycle. With the better knowledge of the ionosphere now available, it is considered likely that this reception was due to the prevalence of sporadic E-layer conditions.

Some years later, in the proximity of the sunspot maximum of 1937, many observations were made of the reception of signals on frequencies in the region of 30 Mc/s, at distances and under conditions which could not be explained either by diffraction of the radio waves round the earth, or by refraction through the lower atmosphere. Such reception was found to be possible during the winter months of November to April or May; and

the conditions soon deteriorated after the period of maximum sunspot activity. These results are now known to be quite consistent with ionospheric conditions prevailing during the maximum phase of sunspot activity, and it is appreciated that the upper limit of frequency used for the observations was set by the apparatus available at the time. As was shown during the succeeding sunspot maximum of 1947, long-distance transmission by way of the F2 layer of the ionosphere has been realized on frequencies as high as 60 Mc/s (wavelength 5 m).[41] Apart from this regular type of transmission it is now recognized that the propagation of these and even higher frequencies may take place either by reflection or by scattering from sporadic regions of ionization in the E layer of the ionosphere, with suitable apparatus used under the appropriate conditions.

In an accompanying paper,[42] F. A. Kitchen and K. W. Tremellen review the circumstances and characteristics of the reflection of v.h.f. radio waves from the ionosphere and the consequent effects on television reception.

(5) WAVE PROPAGATION AT FREQUENCIES ABOVE 300 Mc/s

(5.1) Decimetre Waves (10 to 100 cm)

Mention has already been made of the fact that the provisional allocation of frequencies for television broadcasting in the European Region includes the 470–960-Mc/s band (wavelengths approximately 31–61 cm). Until recently, few systematic investigations of the propagation of waves in this part of the spectrum appear to have been made, although the technique of generating oscillations in the decimetre waveband (10–100 cm) has been studied very actively since 1919.

The possibilities of decimetre waves for communication were appreciated in 1931, when a large-scale public demonstration was given of duplex radio-telephony across the English Channel over a distance of 35 km on a wavelength of 18 cm. Later, G. Marconi[43] carried out a series of tests in the Mediterranean over distances up to 250 km on a wavelength of 57 cm; and in 1933 a radio link was established between the Vatican City and Castel Gondolfo (a distance of 20 km) on a wavelength of 60 cm. In the following year, a decimetre-wave link was opened for commercial purposes between the aerodromes of Lympne in England and St. Inglevert in France, a distance of 56 km, on a wavelength of 17·4 cm. A description of the propagation measurements made over this link has been published by W. L. McPherson and E. H. Ullrich,[44] who observed fluctuations in field strength of up to 40 db, which were largely ascribed to variations in the refractive index of the atmosphere supplemented by the tidal variation of the sea surface, resulting in path changes in the direct and reflected waves arriving at the receiver. It is pertinent to note here that the various stages of the radio-relay link which connected the London and Birmingham television stations in December, 1949, operate on frequencies between 870 and 937 Mc/s.[45] Although the greatest distance between repeater stations on this link is just under 64 km, it will be interesting to know in due course how, if at all, the performance of this relay circuit is affected by propagation characteristics. It is with the view of supplementing the very sparse knowledge available on the propagation of waves in the decimetre waveband in this country that investigations are now being conducted by the Radio Research Organization of the D.S.I.R. in co-operation with the Post Office and the B.B.C.

(5.2) Centimetre Waves (1 to 10 cm)

From about 1940 onwards, the rapid extension of radar technique to centimetre wavelengths provided a great incentive to the study of propagation in the centimetre waveband, with particular reference to wavelengths of about 3 and 9 cm (frequencies of about 3 000 and 10 000 Mc/s). Much of the work conducted in this field, both in this country and elsewhere, was directed towards oversea transmission, but a certain amount of investigation of overland conditions was carried out, and the results of this are likely to prove very valuable in the development of radio links for television purposes.

As has been indicated earlier, in the study of the propagation of radio waves it is often necessary to know the magnitudes of the reflection coefficients of, and the absorption produced by, the various media of the earth's surface. Direct measurements of the reflection coefficient of smooth and rough ground, and of fresh and sea water, have been made at the wavelength of 9 cm by L. H. Ford and R. Oliver.[46] Water is a polar liquid, and dispersion of its dielectric properties occurs in the centimetre waveband; the effect of this dispersion on the reflection coefficient of fresh-water surfaces at wavelengths in the range 1 cm to 10 m has been discussed by J. A. Saxton,[47] and, from an examination of the dielectric properties of sodium-chloride solutions, the same author and J. A. Lane[48] have been able to deduce the reflection and absorption characteristics of sea water at similar wavelengths. Saxton[49] has also shown that it is possible for the reflection coefficients of land and sea surfaces to be modified to an important extent when the surfaces are covered by layers of snow and ice respectively.

Among the various publications describing the results of more general work, reference may be made to an important paper by E. C. S. Megaw,[50] which presents a survey of the experimental work on the propagation of very short waves, and especially of centimetre waves, carried out in this country during the war. Of particular interest in connection with the present paper is the description of the observations made on a wavelength of 9 cm over a land path between Haslemere and Wembley, a distance of 60 km. Under standard atmospheric conditions the path between sender and receiver was clear except for the last mile, where trees and houses formed a barrier elevated about half a degree above the ray path. Allowance being made for the local diffraction loss due to these obstacles, it was found that the mean level of the signal during two or three years was of the same order of magnitude as the estimated standard level. Seasonal variations in this signal level were observed, with a maximum in late summer of the order of 10 db higher than the minimum in winter.

The results of a study of these radio observations in relation to the prevailing meteorological conditions have been published in another paper by R. L. Smith-Rose and Miss A. C. Stickland.[51] It is there shown that the occurrence of clear nights, fog, and the passage of cold fronts across the path of transmission have a marked effect upon the reception conditions, and the frequency of association of these conditions with certain periods of the year may have an appreciable influence on any seasonal variation. For example, the mean hourly value of signal strength over the 60-km path between Haslemere and Wembley may rise by about 15 db on a clear summer night, whereas the incidence of shallow fog following a clear winter night can cause a decrease of signal strength of 20 db or more. In other cases, however, where the fog is deeper and more persistent, the signal strength may increase considerably, presumably owing to the formation of a sharp vertical gradient of refractive index at the top of the fog. These occurrences, and those accompanying the passage of frontal conditions across the path of transmission, are all accompanied by signal fading to a greater or less degree; the rate of fluctuation varies considerably from a very rapid type (several times a minute) to a quasi-periodic type with a period up to half an hour.

In addition to the above work, several more specific investiga-

tions have been conducted on centimetre waves, and the results of these should be of considerable value to those responsible for planning radio links for television and other purposes. Reference has already been made[16, 17] to experiments made on the diffraction of waves between 10 cm and 10 m over hills approximating in contour a cylindrical surface. In an extension of this work, J. S. McPetrie and L. H. Ford[52] have investigated the effect of various obstacles, such as trees and buildings, on transmissions on a wavelength of 9·2 cm. The experiments were made over open and sensibly flat ground, and while small irregularities in ground contour are usually sufficient to cause considerable departures from the values of signal strength computed for a flat surface, such effects present no difficulty in the study of the absorption effect of obstacles over relatively short distances of transmission. Many of the obstacles investigated absorb so much of the radiation passing through them that it is necessary to treat them as opaque bodies round which diffraction takes place. For example, transmission through the wall, 23 cm thick, of a small dwelling house involved a loss of 12 db when the wall was dry, and of more than 40 db after the wall was soaked in water. These values correspond to a transmission loss of from 0·5 to 2 db per centimetre thickness of brick and plaster, and the same figures are also found to apply to dry and wet wood, while somewhat higher values were observed for roofing of tile and slate. In discussing the results of their measurements, the authors conclude that those obstacles which should in general be regarded as opaque to the transmission of centimetre waves include (a) rows of trees in leaf, if more than two in depth, (b) screens of leafless trees, if so dense that the sky-line is not visible between them, (c) trunks of trees, whether in leaf or not, (d) walls of masonry 20 cm or more in thickness, and (e) any but the slightest wooden buildings, particularly those containing partitions.

In considering the transmission of waves through the atmosphere itself, J. W. Ryde[53] has investigated theoretically the attenuation of centimetre waves due to fog, cloud, rain, hail and desert sand- and dust-storms. He concluded that for wavelengths between 3 and 10 cm the attenuation produced by atmospheric phenomena is small, except under conditions of heavy precipitation; the effects are, however, sufficiently large to need serious consideration when the distance of transmission is great. For example, in a fog with a visual range of 30 m, the attenuation for a wavelength of 3 cm may be about 0·25 db/km. Similar values apply to conditions of steady rain as experienced in this country; but the attenuation may rise to several times this value for short periods during heavy thunderstorms.

Where radio links for television have to cross sea areas, the results of investigations carried out during the war will be of value. Papers to which reference has already been made[50, 51] describe the results of a long series of observations made on wavelengths of 3 and 9 cm over an all-sea path across Cardigan Bay, 92 km long. The installation of two sending and two receiving stations at different heights provided four radio links, of which one was over a clear optical path, and was of the type most likely to be used in any practical design for a reliable service. Over this path the received signal-strength was generally a few decibels below that expected for the free-space-radiation condition, with variations not exceeding 10 db about the mean value. These variations, which were much greater for a wavelength of 3 cm than for one of 9 cm, were attributed mainly to effects of phase interference between the direct ray and that reflected off the sea surface, rather than to any variation in atmospheric absorption along the path. For the non-optical paths, the mean level of field was well below the free-space level —of the order of 40–50 db for the lowest link, for which the distance was about 2·2 times the optical range. Over these

paths the signal level was, for about 70–80% of the time, at least as great as that expected for normal atmospheric-gradient conditions, taking account both of refraction in the atmosphere and of diffraction round the curved surface of the earth. As in the case of transmission over land, the signal strength varied considerably with atmospheric conditions, to such an extent that on occasions it approached, and even slightly exceeded, the free-space value. Anticyclonic weather gave rise to good signals, and these were especially strong but very variable in summer conditions.

These broad conclusions have been supported by several other investigations carried out in various parts of the world, and a considerable amount of research has been, and still is, in progress with a view to establishing a closer understanding of the relation between the radio phenomena and the meteorological conditions at a given time and a given place.

(6) CONCLUSIONS

This review is intended to indicate the extent to which investigations of radio propagation conditions have provided fundamental information of direct use to the engineer responsible for planning and installing television services. In the lowest band of frequencies, to which television broadcasting in Europe is at present confined, the expected service area of a station can be specified fairly accurately from an inspection of the terrain and a knowledge of the factors which influence wave propagation in the vicinity of the proposed site. While some further investigation is still required over various types of terrain, much useful information already exists on the propagation conditions at distances of several hundred kilometres from the sending station. This knowledge is of great use on both a national and an international basis for specifying the geographical separation necessary for stations operating in the same channel to provide services free from mutual interference.

A frequency band of several hundred megacycles per second will undoubtedly be required for future services, particularly if these are to provide transmissions of improved definition or in colour. In this range our knowledge of wave propagation appears to be somewhat scanty, although the subject is already under active investigation.

For the still higher frequencies, ranging up to 10 000 Mc/s, a considerable amount of investigation has already yielded a general understanding of the propagation phenomena involved; and this knowledge and experience form a useful guide to the engineer responsible for transmitting television signals, usually for radio-link purposes, on such carrier frequencies. In this connection, an accompanying paper by W. J. Bray and R. L. Corke[55] describes a technique which has been developed for examining the merits of sites chosen for the installation of radio-link equipment.

Finally, while brief reference has been made to outstanding work carried out elsewhere, the intention throughout the paper has been to keep in mind the title of this Convention, and portray chiefly the contribution which British research has made to our present knowledge of radio-wave propagation and its application to the development of a television broadcasting service.

(7) ACKNOWLEDGMENT

(8) REFERENCES

(1) SMITH-ROSE, R. L., and McPETRIE, J. S.: "The Attenuation of Ultra-Short Radio Waves due to the Resistance of the Earth," *Proceedings of the Physical Society*, 1931, **43**, p. 592.

(2) McPETRIE, J. S., and SAXTON, J. A.: "An Experimental Investigation of the Propagation of Radiation having Wavelengths of 2 and 3 Metres," *Journal I.E.E.*, 1940, **87**, p. 146.

(3) McPETRIE, J. S.: "A Determination of the Electrical Constants of the Earth's Surface at Wavelengths of 1·5 0·46 m," *Proceedings of the Physical Society*, 1934, **46**, p. 637.

(4) SMITH-ROSE, R. L.: "The Electrical Properties of Soil at Frequencies up to 100 Megacycles per Second," *ibid.*, 1935, **47**, p. 923.

(5) McPETRIE, J. S., and SAXTON, J. A.: "The Electrical Properties of Soil at Wavelengths of 5 metres and 2 metres," *Journal I.E.E.*, 1945, **92**, Part III, p. 256.

(6) McPETRIE, J. S.: "The Reflection Coefficient of the Earth's Surface for Radio Waves," *ibid.*, 1938, **82**, p. 214.

(7) McPETRIE, J. S., and STICKLAND, (Miss) A. C.: "Reflection Curves and Propagation Characteristics of Radio Waves along the Earth's Surface," *ibid.*, 1940, **87**, p. 135.

(8) MILLINGTON, G.: "Ground-Wave Propagation over an Inhomogeneous Smooth Earth," *Proceedings I.E.E.*, 1949, **96**, Part III, p. 53.

(9) MILLINGTON, G., and ISTED, G. A.: "Ground-Wave Propagation over an Inhomogeneous Smooth Earth: Part 2. Experimental Evidence and Practical Implications," *ibid.*, 1950, **97**, Part III, p. 209.

(10) ECKERSLEY, T. L.: "Ultra-Short-Wave Refraction and Diffraction," *Journal I.E.E.*, 1937, **80**, p. 286.

(11) MILLINGTON, G.: "The Diffraction of Wireless Waves round the Earth," *Philosophical Magazine*, 1939, **27**, p. 517.

(12) C.C.I.R.: "Report of Committee on Radio Wave Propagation," *Proceedings of the Institute of Radio Engineers*, 1938, **26**, p. 1193.

(13) VAN DER POL, B., and BREMMER, H.: "The Propagation of Radio Waves over a Finitely Conducting Spherical Earth," *Philosophical Magazine*, 1937, **24**, p. 141 and p. 825; 1938, **25**, p. 817; 1939, **27**, p. 261.

(14) ECKERSLEY, T. L.: "Studies in Propagation," Transactions of Marconi International Congress, Rome, 1948, pp. 78–96.

(15) DOMB, C., and PRYCE, M. H. L.: "The Calculation of Field Strengths over a Spherical Earth," *Journal I.E.E.*, 1947, **94**, Part III, p. 325.

(16) McPETRIE, J. A., and SAXTON, J. A.: "Diffraction of Ultra-Short Radio Waves," *Nature*, 1939, **144**, p. 631, and 1942, **150**, p. 292.

(17) McPETRIE, J. S., and FORD, L. H.: "An Experimental Investigation on the Propagation of Radio Waves over Bare Ridges in the Wavelength Range 10 cm to 10 m," *Journal I.E.E.*, 1946, **93**, Part IIIA, p. 527.

(18) LAWSON, D. I.: "Multipath Interference in Television Transmission," *ibid.*, 1945, **92**, Part III, p. 125.

(19) HOPKINS, H. G., and HORNER, F.: "Direction-Finding Site Errors at Very High Frequencies," *ibid.*, 1949, **96**, Part III, p. 321.

(20) HORNER, F.: "Scattering of Radio Waves by Metal Wires and Sheets," *ibid.*, p. 333.

(21) RAYLEIGH, LORD: "On the Theory of Stellar Scintillation," *Philosophical Magazine*, 1893, **36**, p. 129.

(22) FLEMING, J. A.: "On Atmospheric Refraction and its Bearing on the Transmission of Electromagnetic Waves round the Earth's Surface," *Proceedings of the Physical Society*, 1914, **26**, p. 318.

(23) BAKER, T. Y.: "On the Refraction of Electro-magnetic Waves in a Spherically Stratified Medium," *Philosophical Magazine*, 1927, **4**, p. 955.

(24) (a) ENGLUND, C. R., CRAWFORD, A. B., and MUMFORD, W. W.: "Further Results of a Study of Ultra-Short-Wave Transmission Phenomena," *Bell System Technical Journal*, 1935, **14**, p. 369.

(b) ENGLUND, C. R., CRAWFORD, A. B., and MUMFORD, W. W.: "Ultra-Short-Wave Transmission and Atmospheric Irregularities," *ibid.*, 1938, **17**, p. 489.

(25) BEST, A. C.: "A Standard Radio Atmosphere for Microwave Propagation," Physical Society and Royal Meteorological Society: Report of a Conference on "Meteorological Factors in Radio-Wave Propagation," 1946, pp. 267–273.

(26) "Glossary of Terms used in Radio Propagation," B.S. 204: 1949, Supplement No. 2.

(27) TAGHOLM, L. F., and ROSS, G. I.: "The Selection and Testing of Sites for Television Transmitters in the United Kingdom" (see page 300).

(28) MACNAMARA, T. C., and BIRKINSHAW, D. C.: "The London Television Service," *Journal I.E.E.*, 1938, **83**, p. 729.

(29) BEVAN, P. A. T., and PAGE, H.: "The Sutton Coldfield Television Broadcasting Station," *Proceedings I.E.E.*, 1951, **98**, Part III, p. 416.

(30) KIRKE, H. L., ROWDEN, R. A., and ROSS, G. I.: "A V.H.F. Field-Strength Survey on 90 Mc/s," *ibid.*, p. 343.

(31) WILMOTTE, R. M.: "Polycasting," *Proceedings of the Institute of Radio Engineers*, 1951, **39**, p. 740.

(32) (a) JOUAUST, R.: "Les Ondes Très Courtes," *L'Onde Électrique*, 1930, **9**, p. 5.

(b) JOUAUST, R.: "Some Details relating to the Propagation of Very Short Waves," *Proceedings of the Institute of Radio Engineers*, 1931, **19**, p. 479.

(33) Department of Scientific and Industrial Research. Report of the Radio Research Board for the Year 1931, pp. 30–31 (H.M. Stationery Office, 1931).

(34) (a) HULL, R. A.: "Air-Mass Conditions and the Bending of Ultra-High-Frequency Waves," *Q.S.T.*, June 1935, **19**, p. 13.

(b) HULL, R. A.: "Air Wave Bending of Ultra-High-Frequency Waves," *ibid.*, May 1937, **21**, p. 16.

(c) FRIEND, A. W.: "A Summary and Interpretation of Ultra-High-Frequency Wave-Propagation Data collected by the late Ross A. Hull," *Proceedings of the Institute of Radio Engineers*, 1945, **33**, p. 358.

(35) SMITH-ROSE, R. L., and STICKLAND, (Miss) A. C.: "A Study of Propagation over the Ultra-Short-Wave Radio Link between Guernsey and England on Wavelengths of 5 and 8 metres (60 and 37·5 Mc/s)," *Journal I.E.E.*, 1943, **90**, Part III, p. 12.

(36) BOOKER, H. G.: "Elements of Radio Meteorology: How Weather and Climate cause Unorthodox Radar Vision beyond the Geometrical Horizon," *ibid.*, 1946, **93**, Part IIIA, p. 69.

(37) (a) SAXTON, J. A.: "The Propagation of Metre Radio Waves beyond the Normal Horizon. Part 1: Some Theoretical Considerations, with Particular Reference to Propagation over Land," *Proceedings I.E.E.*, 1951, **98**, Part III, p. 360.

(b) SAXTON, J. A., LUSCOMBE, G. W., and BAZZARD, G. H.: "The Propagation of Metre Radio Waves beyond the Normal Horizon. Part 2: Experimental Investigations at Frequencies of 90 and 45 Mc/s," *ibid.*, p. 370.

(38) MEGAW, E. C. S.: "Scattering of Electromagnetic Waves by Atmospheric Turbulence," *Nature*, 1950, **166**, p. 1100.

(39) SAXTON, J. A.: "Long-Distance Propagation in Relation to Television in the United Kingdom" (see page 294).

(40) (a) Department of Scientific and Industrial Research. Report of the Radio Research Board for the year 1931, p. 31.
(b) Ibid. Report of the Radio Research Board for the period 1st January, 1932, to 30th September, 1933, p. 62.

(41) (a) HEIGHTMAN, D. W.: "Transatlantic and Middle-East: Two-way on 50 Mc/s," R.S.G.B. Bulletin, 1947, 23, pp. 106–108.
(b) NAISMITH, R.: "Six-Metre Transatlantic Signals," Wireless World, 1947, 53, p. 186.

(42) KITCHEN, F. A., and TREMELLEN, K. W.: "Ionospheric Influences in Television Reception" (see page 290).

(43) MARCONI, G.: "Radio Communications by means of Very Short Electric Waves," Proceedings of the Royal Institution of Great Britain, 1933, 27, p. 509.

(44) McPHERSON, W. L., and ULLRICH, E. H.: "Micro-Ray Communication," Journal I.E.E., 1936, 78, p. 629.

(45) CLAYTON, R. J., ESPLEY, D. C., GRIFFITH, G. W. S., and PINKHAM, J. M. C.: "The London–Birmingham Television Radio-Relay Link," Proceedings I.E.E., 1951, 98, Part I, p. 204.

(46) FORD, L. H., and OLIVER, R.: "An Experimental Investigation of the Reflection and Absorption of Radiation of 9-cm Wavelength," Proceedings of the Physical Society, 1946, 58, p. 265.

(47) SAXTON, J. A.: "Electrical Properties of Water: Reflection Characteristics of Water Surfaces at V.H.F.," Wireless Engineer, 1949, 26, p. 288.

(48) SAXTON, J. A., and LANE, J. A.: "The Anomalous Dispersion of Water at Very High Radio Frequencies," Physical Society and Royal Meteorological Society: Report of a Conference on "Meteorological Factors in Radio-Wave Propagation," 1946, pp. 278–292.

(49) SAXTON, J. A.: "Reflection Coefficient of Snow and Ice at V.H.F.," Wireless Engineer, 1950, 27, p. 17.

(50) MEGAW, E. C. S.: "Experimental Studies of the Propagation of Very Short Radio Waves," Journal I.E.E., 1946, 93, Part IIIA, p. 79.

(51) SMITH-ROSE, R. L., and STICKLAND, (Miss) A. C.: "An Experimental Study of the Effect of Meteorological Conditions upon the Propagation of Centimetric Radio Waves." Physical Society and Royal Meteorological Society: Report of a Conference on "Meteorological Factors in Radio-Wave Propagation," 1946, pp. 18–37.

(52) McPETRIE, J. A., and FORD, L. H.: "Some Experiments on the Propagation over Land of Radiation of 9·2-cm Wavelength, especially on the Effect of Obstacles," Journal I.E.E., 1946, 93, Part IIIA, p. 531.

(53) (a) RYDE, J. W.: "The Attenuation of Centimetre Radio Waves and the Echo Intensities resulting from Atmospheric Phenomena," ibid., p. 101.
(b) RYDE, J. W.: "The Attenuation and Radar Echoes Produced at Centimetre Wavelengths by Various Meteorological Phenomena." Physical Society and Royal Meteorological Society: Report of a Conference on "Meteorological Factors in Radio-Wave Propagation," 1946, pp. 169–188.

(54) C.C.I.R.: "Ground-Wave Propagation Curves below 10 Mc/s," Documents of the Sixth Plenary Assembly, Geneva 1951, 1, pp. 38–49.

(55) BRAY, W. J., and CORKE, R. L.: "A Technique for 4 000-Mc/s Propagation Testing for Radio-Relay Systems" (see next page).